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Patentanmeldung Nr. Patent application No. Demande de brevet n°

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Thin-Film Bulk Acoustic Wave Ladder Filter with Fan-shaped

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DESCRIPTION**Thin-Film Bulk Acoustic Wave Ladder Filter with Fan-shaped**

The present invention relates generally to filters, and in particular to filters constructed using bulk acoustic wave resonators. Such filters may be used in communications
5 equipment as band pass filters which enable selection of a frequency band in which transmission channels are located, and with rejection of frequencies outside the band of interest. The invention also relates to communications equipment (for example, a radio frequency receiver and/or transmitter) comprising such filters.

- 10 High-performance radio-frequency (RF) filters typically use high dielectric constant ceramic resonators or surface acoustic wave resonators. The former devices are rather bulky, whereas the latter are smaller but have higher insertion loss (generally >3 dB) and generally rather poor stop-bands. As a result, neither provides an ideal solution for channel band selection in small communications devices such as mobile phones. Filters
15 for such applications need deep stop-bands to reject unwanted signals, as well as low pass-band insertion loss (typically <2 dB) to achieve adequate signal-to-noise ratio. There is therefore a requirement for very small resonators with high Q-factor (typically >500). To achieve this aim, with potential for integration on silicon, thin-film bulk-acoustic-wave (BAW) resonators have been proposed. These are applicable to the
20 frequency range 0.5 to 10 GHz, and are therefore appropriate for the third generation mobile telephony standard, as well as for already established wireless standards, such as GSM, W-CDMA, Bluetooth, HomeRF, DECT and GPS.

- The need for low insertion loss and high stop-band attenuation can not be achieved with a single resonator. Filters are therefore typically made up of a number of resonators, and
25 a conventional thin-film BAW filter configuration is a ladder construction, shown in simplified schematic form in FIG. 8. This has alternating series sections and shunt sections, each of which can be a single resonator, or one or more resonators on the same frequency connected in series or parallel (which is electrically equivalent). The anti-

resonant frequency of the shunt element is chosen to be the resonant frequency of the series elements to provide minimum insertion loss at that frequency.

The individual resonators are typically arranged as so-called solidly-mounted resonators (SMRs), an example of which is illustrated in FIG. 1. The required
5 conversion between electrical and mechanical energy is achieved by a layer of piezoelectric material (for example zinc oxide, aluminium nitride, PZT, PLZT) between two metal layers in which electrodes are formed. The piezoelectric material is provided over one or more acoustically mismatched layers, which are mounted on an insulating substrate, for example glass. The acoustically mismatched layers act to reflect the
10 acoustic wave which results from resonance of the piezoelectric layer at the resonant frequency.

In FIG. 2, a number of high impedance layers and low impedance layers are shown. Porous silicon oxide (aerogel) may be used for the low-impedance layers, and a single layer may in fact be adequate to achieve sufficiently high Q, due to the very low
15 acoustic impedance of this material. The high impedance layers may comprise tungsten.

Ladder filter arrangements such as shown in FIG. 8 have demonstrated good performance, for example less than 2 dB insertion loss and very low-level of spurious
20 response. However, there are also some disadvantages, which can be understood from an approximate electrical equivalent circuit of the resonator, shown in FIG. 3.

C_o is an (unwanted) static capacitance of the resonator, whereas C_m , L_m and R_m characterise the mechanical resonance. These are, respectively, the motional capacitance, motional inductance and motional resistance of the resonator. The
25 resonator appears as a pure capacitor C_o at frequencies removed from the resonance (except at other significant mechanical resonances such as harmonics, which are not accounted for in this simple model). In designs reported to date, the shunt and series resonators have similar areas, and therefore similar static capacitances. This gives only

about 6 dB attenuation, in the frequency bands to be rejected by the filter (the "stop-band"), per combination of series and shunt sections. This is the result of the static capacitance of each resonator. A T-section, comprising two series connected resonators and an intermediate shunt resonator may be considered as the basic building block of a ladder filter. A single resonator element is then at the input and output of the filter, and the intermediate series resonators elements each comprise two series connected resonator elements.

To achieve the desired low pass-band insertion loss and high stop-band insertion loss, each individual building block should meet these two requirements. Although increasing the number of sections adds to the stopband loss (as required), this also increases pass-band loss (and also the overall filter size). The pass-band and stop-band requirements therefore conflict with each other. Typically, several such building blocks are required for even moderate stop-band rejection. Consequently, both the area occupied and the insertion loss in the pass-band are increased without improving filter selectivity.

It has been recognised, for example in U.S. Pat. No. 5,471,178, that the stop band performance for a ladder filter is determined in part by the static capacitance ratio between the series and shunt resonators, as the resonators act as a capacitive voltage divider at frequencies removed from the resonant frequencies.

RF filters based on thin-film bulk-acoustic-wave (BAW) resonators are being developed for applications such as mobile phones and wireless connectivity. The advantage of BAW technology is that devices are small, have good power handling (> 1 W), cover the frequency range 1-20 GHz, and can exploit wafer-scale processing and packaging on silicon. Alternative technologies are ceramic electromagnetic (EM) wave filters and surface-acoustic-wave (SAW) filters. The former are relatively large and expensive for equivalent frequencies, while the latter require single-crystal materials such as lithium tantalate or quartz, are limited in practice to frequencies below about 2 GHz, and also have limited power-handling capability.

RF filters are typically required to have very low insertion loss, due to requirements such as receiver sensitivity and transmitter power consumption. Here, a method is proposed for achieving minimal insertion loss in thin-film BAW filters, based on an understanding of the relationship between particular loss mechanisms in resonators and the role that each resonator plays in filter performance.

This understanding leads to the principle claim of this proposal, which is a fan-shaped filter layout in which shunt resonators have unity aspect ratio and series resonators have aspect ratio significantly different from unity.

10

A BAW resonator is essentially an acoustic cavity comprising a piezoelectric layer sandwiched between metal electrode layers. When an alternating electric signal is applied across these electrodes the energy is converted to mechanical form and a standing acoustic wave is excited. The principle mode of vibration in practical thin-film resonators is the fundamental thickness-extensional (TE) acoustic mode, i.e. vibration is normal to the layers. Two main types of resonator have been studied. In the first of these, the film BAW resonator (FBAR) [1], a thin membrane forms the cavity as shown in Fig. 1. In the second, the solidly-mounted BAW resonator (SBAR) [2] shown in Fig. 2, the lower free surface of the membrane is replaced by a set of acoustically mismatched layers, which act to reflect the acoustic wave. This concept is analogous to the Bragg reflector in optics. The reflector layers are deposited on a solid substrate, typically silicon, so this structure is physically more robust than the FBAR. Typical dimensions and materials are shown in both figures. Electrical connection to the bottom electrode may be through a via, as shown in Fig.1. Alternatively, the via may be avoided by having the bottom electrode electrically floating, and forming two resonators in series, as shown in Fig.2. With appropriate areas the two approaches are to first order electrically identical, and each may be used with either the FBAR or SBAR configuration.

25

A commonly-used electrical equivalent circuit of a BAW resonator is shown in Fig.3. C_o , C_1 , L_1 and R_1 respectively characterise the static capacitance, motional capacitance, motional inductance and motional resistance of the resonator itself, and together form the so-called Butterworth-Van Dyke model. The remaining components are electrical parasitics. The three resistors characterise distinct types of energy loss: ohmic loss in the electrodes and interconnect (R_s), loss due to stray electric fields in the silicon substrate (R_p), and mechanical losses associated with the resonance (R_1). Dielectric loss is typically negligible.

These loss mechanisms are central to what is proposed here. The equivalent-circuit model is useful for first-pass design of filters (and other circuits using BAW resonators). A more physically-based representation of a BAW resonator is the Novotny-Benes model. This provides a solution of the field equations in one dimension (1D). It is assumed that the mechanical and electrical fields have significant spatial variations only in the thickness direction. Since the lateral dimensions of a typical resonator are much greater than layer thicknesses this is a reasonable approximation. The measured conductance (real part of admittance) of a typical BAW resonator is compared over a wide band with predictions by both models in Fig.4. The level of agreement for the susceptance (imaginary part) is similar. The electrical parasitic components R_s , L_s , R_p and C_p are included in both models. Most, but not all, features of the response are predicted by the 1D physical model.

For filter design, two characteristic frequencies are particularly important: the resonance f_r and anti-resonance f_a , the frequencies of maximum and minimum admittance respectively. For high Q-factor resonances these are very close to the maximum and minimum of conductance. In this example they are at approximately 1.985 GHz and 2.03 GHz respectively. Fig. 5 shows an expanded view of the curves shown in Fig. 4 close to f_r . The detailed behaviour near resonance is shown to be quite accurately predicted by both models. Fig.6 shows the very fine detail near f_a and this demonstrates a small but significant area of disagreement. The measured response clearly shows some

ripple and additional conductance (i.e. loss) near f_a . This is predominantly due to closely-spaced weakly-excited modes which contain transverse field components, and fields with transverse as well as normal spatial variation. They are not accounted for in either of the above models. However, they cannot be ignored in filter design because
5 energy loss at anti-resonance has a serious impact on filter performance. It would be possible to include these additional unwanted modes by extending the physical model to 2D or 3D, but they can also be approximated in the equivalent-circuit model as shown in Fig.7, where each of the parallel branches ($j = 2, 3 \dots J$) corresponds to an unwanted mode. The j -th mode is then characterised by the motional parameters C_j , L_j and R_j .

10

BAW filters are implemented by inter-connecting thin-film BAW resonators. One of the preferred architectures is the ladder filter, for which an example schematic circuit is shown in Fig.8.

15

The number of ladder sections (each comprising series and shunt resonators) depends on the desired selectivity and other design considerations. For RF filters the required very low insertion loss may be achieved by designing the series resonators to have very high conductance (ideally infinite) at the filter center frequency f_o , and the shunt
20 resonators to have very low conductance (ideally zero) at f_o . For minimum possible loss both f_r of the series resonators and f_a of the shunt resonators should be coincident with f_o . However, for certain applications it is possible to sacrifice some insertion loss performance in order to achieve wider bandwidth. In either case the conductance of the series resonators at f_r should be as high as possible (typically > 1 S for a 50 ohm filter),
25 and the conductance of the shunt resonators at f_a should be as low as possible (typically < 1 mS for a 50 ohm filter). The prototype resonator used as an example here approaches these targets.

In high Q-factor devices energy loss near resonance or anti-resonance is only a very small fraction of stored energy. This cannot be accurately predicted from first principles, partly because sufficiently accurate material loss data is not available, and partly (in the case of the two above models) the loss mechanisms are not included.

5 However, realistic resistors (and other components) in the equivalent-circuit model in Fig. 3 may be readily extracted from measurement by using simple circuit theory and adjusting the component values to give the agreement shown in Figs. 4 and 5. For example, assuming high Q-factor, circuit theory leads to the relationships $f_r \approx 1/\sqrt{L_1 C_1}$ and $f_a \approx \sqrt{(C_o + C_1)/(L_1 C_1 C_o)}$. Substrate losses are typically very low giving a very

10 high value of R_p , and therefore the values of conductance at f_r and f_a are approximately $1/[R_s + R_1]$ and $1/[R_s + 1/(4\pi^2 C_o^2 R_1)]$ respectively. In principle, component values for the extended circuit model in Fig. 7 could be extracted by matching the ripple near f_a shown in Fig. 6. It is found in practice that, in the above expressions for conductance, the first term in the denominator (i.e. R_s) dominates at f_r and the second term (i.e.

15 $1/(4\pi^2 C_o^2 R_1)$) dominates at f_a . The expressions for conductance at f_r and f_a given by the extended circuit are much more complex, but the same general conclusion that electrical loss dominates at f_r and mechanical loss at f_a is still reached. Therefore optimum low-loss filter design implies different criteria for the design of the series and shunt resonators. Optimum design is not achieved by applying the same design criteria to all

20 resonators.

From the above discussion it follows that, for series resonators minimizing conductor resistance is the most important consideration. On the other hand, for shunt resonators minimizing mechanical loss at anti-resonance is the most important consideration.

25 Clearly, the mechanical loss associated purely with the wanted mode must be minimized, i.e. R_1 must be as small as possible. However, referring to the equivalent circuit in Fig. 7, even if R_1 is indeed small, the contribution to a shunt resonator's conductance at f_a from its j^{th} (unwanted) mode will be significant if the frequency is close to f_a and the value of R_j is sufficiently high (i.e. its Q-factor is sufficiently low) such that

30 its contribution adds significantly to that of the wanted mode. The measurement in Fig.

6 demonstrates this clearly. In principle, all unwanted modes contribute to some extent towards increasing the admittance at anti-resonance, so for shunt resonators loss of energy into unwanted modes must be minimized.

- 5 In filter design resonator area is fixed by the desired impedance (which is inversely proportional to area). Second-order aspects of behaviour can however be influenced by resonator shape. Excitation of unwanted modes is generally associated with electrode edges, so mechanical energy lost is strongly related to the length of the perimeter of the resonator. Stored energy, on the other hand, is related to resonator area. Therefore Q-
- 10 factor at anti-resonance is maximized for a resonator shape that maximizes the ratio of area to perimeter. This has been confirmed experimentally. Shunt resonators should therefore ideally be circular. If, for any reason such as compactness of layout, a rectangular shape is preferred, then shunt resonators should be square. Any resonator can in principle be split into more than one in series or parallel. Applying the criteria
- 15 discussed here shunt resonators should not be divided into parallel devices since these will have smaller area, but creating say two in series as in Fig.1 is advantageous since each then has twice the area of the original.

- The above considerations are much less significant in the design of the series
- 20 resonators, for which the mechanical loss is typically substantially less than the conductor loss. Thus, the resistance of the path taken by the electrical current through the chain of series resonators should be minimized. This may be achieved by making the dimension corresponding to this longitudinal direction short, with the transverse dimension being correspondingly long, so as to retain the required impedance level. In
- 25 practice, there will be a limit to aspect ratio, because beyond a certain value corresponding to very narrow resonators the mechanical loss at f_r will become significant compared to the electric loss.

- An example of a physical layout of top and bottom electrode layers based on these
- 30 design criteria is shown in Fig. 10, with the corresponding layer structure shown

schematically in Fig.9. Resonators are defined by the areas of overlap of the top metal layer (dark grey - 1) and bottom metal layer (light grey - 2). The different aspect ratios required for optimum performance of the series resonators (A) and shunt resonators (B) are taken into account in the fan-shaped layout shown. Areas on the left and right sides of the layout where the top metal does not overlap the bottom are input, output and ground pads. Typically these area have an additional thick metal layer applied. This further reduces series resistance and facilitates connections (e.g. flip-chip). Where possible edges of areas of overlap are defined by electrode edges in the top layer. For such edges, there is no physical discontinuity in the piezoelectric layer, so conversion of energy into unwanted modes should at least be minimized. The variant in Fig. 11 has elongated holes in the top layer to increase the proportion of the shunt resonator edge length defined in this way. (Since holes also increase resistance they are likely to be counter-productive for the series resonators, and are therefore omitted from this part of the layout.) Another variant, shown in Fig.12, has rounded corners to further reduce abrupt physical discontinuities. Variants with circular shunt electrodes, and/or shunt resonators implemented using two or more in series may also be considered, although the implications for total area and degree of fan-out must be taken into account. In addition to the unwanted modes excited by the resonator itself, other modes may be excited by stray electric fields penetrating the piezoelectric layer. Therefore, the length of interconnect lines in either of the metal layers should be as short as possible in order to minimize both this source of energy loss and resistive losses.

The active area of FBAR device is defined by area overlapping area of the first electrode, the PZT material layer and the second electrode.

CLAIMS:

1. A ladder filter comprising a plurality of bulk acoustic wave resonators, the resonators comprising a plurality of series resonators in series between an input port and an output port of the filter, and one or more shunt resonators each connected between a junction between two series resonators and a common terminal, the series resonators comprising
5 an input series resonator connected to the input port and an output series resonator connected to the output port, and wherein the shunt resonators are designed to satisfy: an unity aspect ratio and wherein the series resonators are designed to satisfy an aspect ration different from unity.

10

2. A radio frequency band pass filter comprising a ladder filter as claimed in claim 1 .

3. A radio frequency receiver and/or transmitter device comprising a band pass filter as claimed in claim 8 .

15

ABSTRACT:**Thin-film BAW ladder filter with fan-shaped layout**

A ladder filter comprising a plurality of bulk acoustic wave resonators, the resonators comprising a plurality of series resonators in series between an input port and an output
5 port of the filter, and one or more shunt resonators each connected between a junction between two series resonators and a common terminal, the series resonators comprising an input series resonator connected to the input port and an output series resonator connected to the output port, and wherein the shunt resonators are designed to satisfy:
an unity aspect ratio and wherein the series resonators are designed to satisfy an aspect
10 ration different from unity.

Fig. 9

1/6

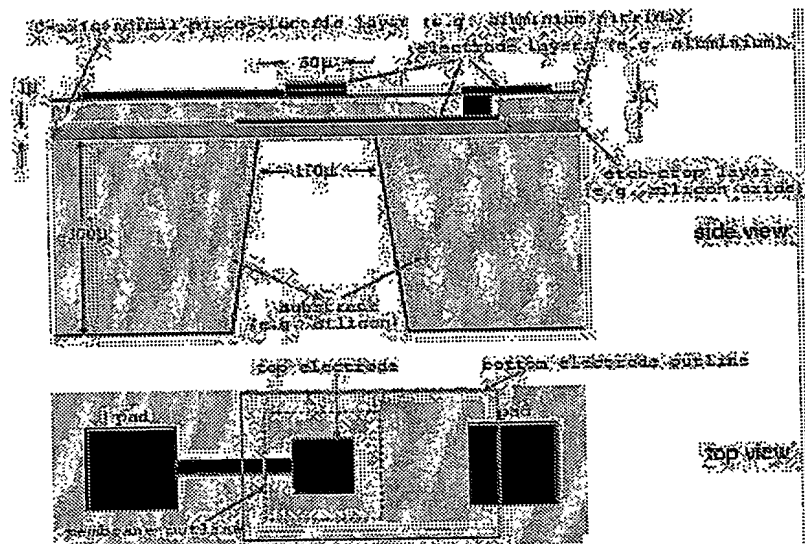


Fig. 1

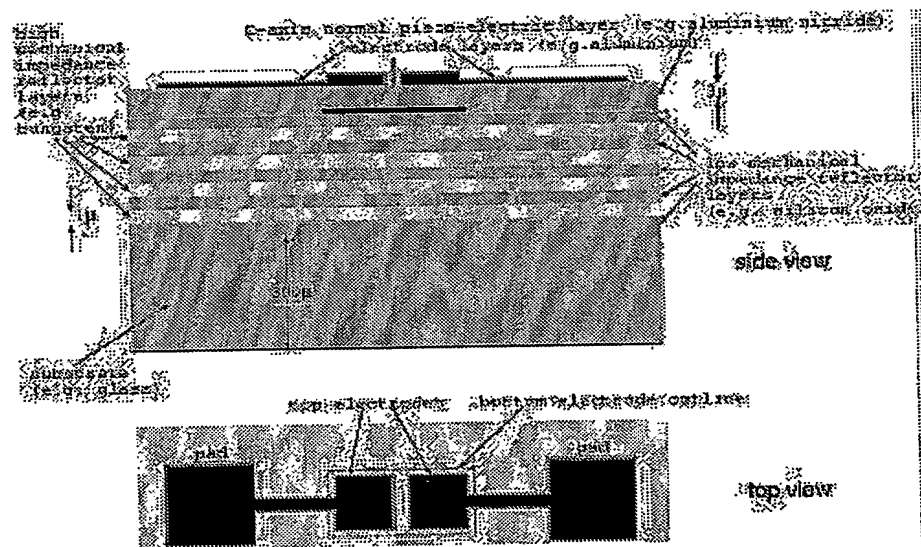


Fig. 2

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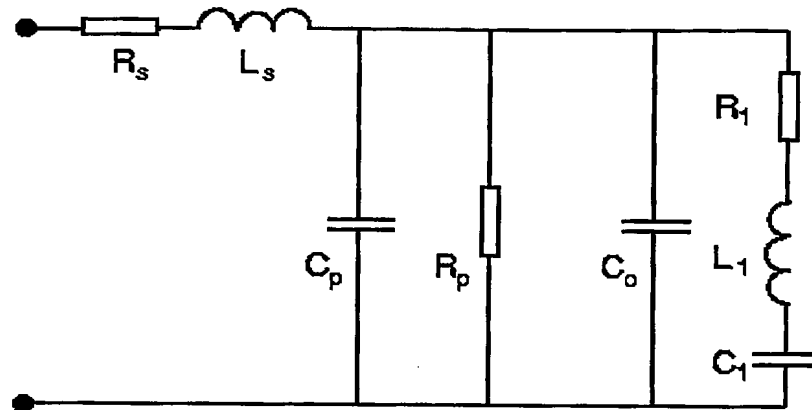


Fig. 3

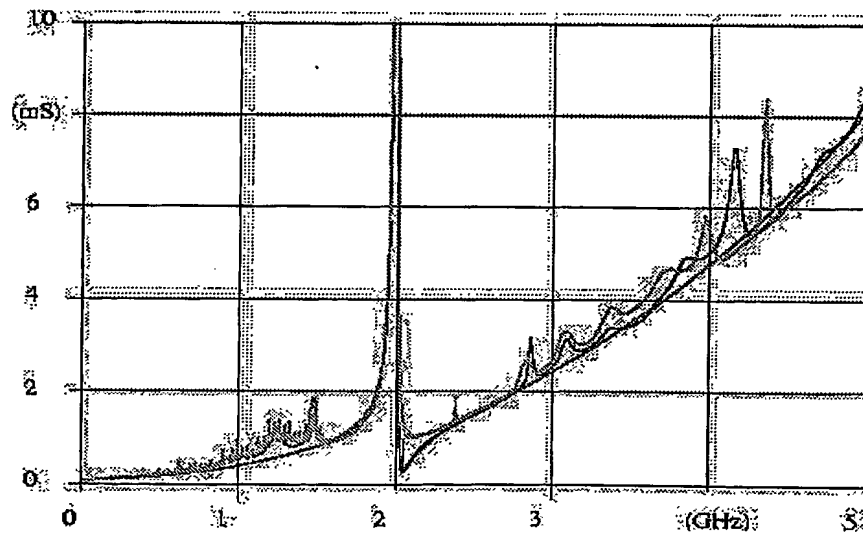


Fig. 4

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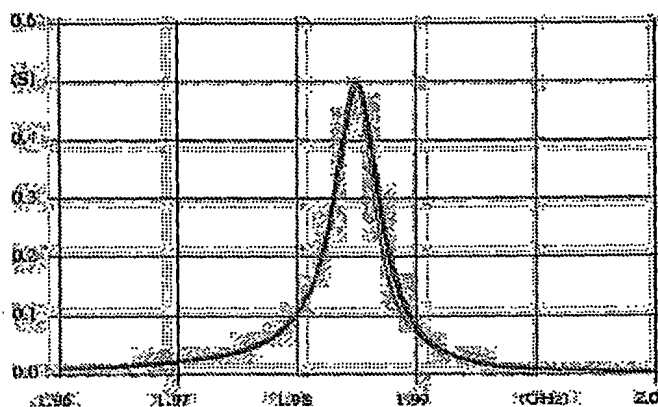


Fig. 5

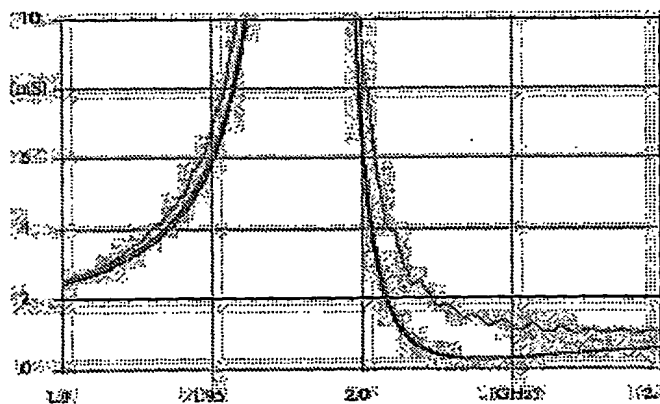


Fig. 6

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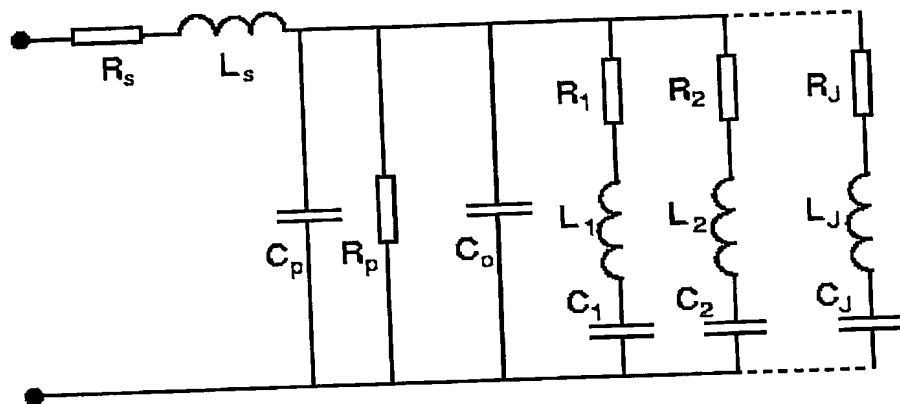


Fig. 7

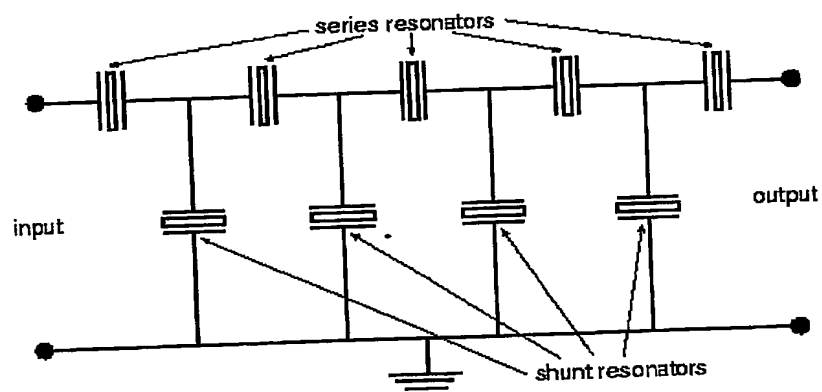


Fig. 8

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Cross-section A-A

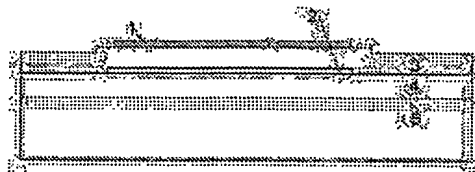


Fig. 9

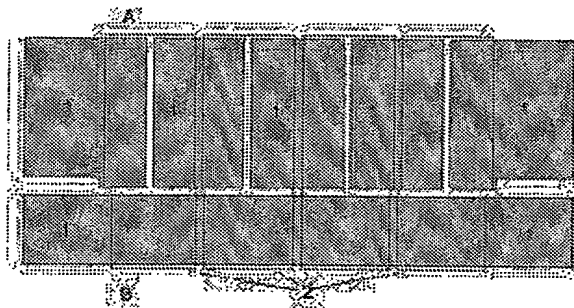


Fig. 10

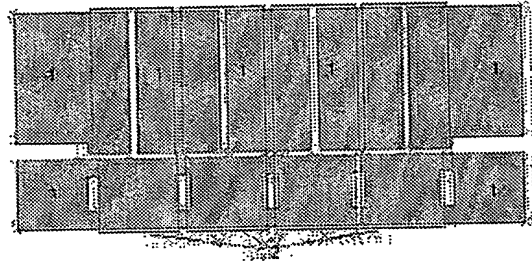


Fig. 11

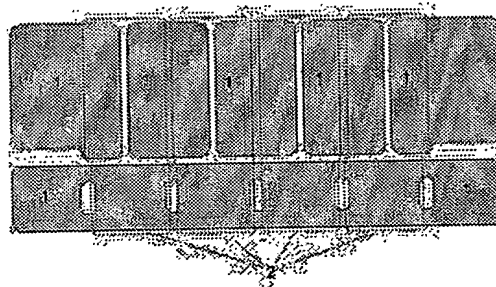


Fig. 12

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